

# Wave Propagation in Granular Media Including Marine Sediments

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## LONG-TERM GOALS

The long term objective is to characterize the wave properties of marine sediments, both experimentally and theoretically, in the frequency band between 100 Hz and 100 kHz.

## OBJECTIVES

Our sediment research includes four main thrusts: (1) at-sea experiments, including the development of novel inversion techniques, to determine the wave properties of sediments; (2) theoretical analyses, including a) construction of a physics-based analytical model to describe the wave properties of sediments, b) analysis of wave propagation from a moving source in a viscous medium and c) rationalization of Biot's theory of waves in porous media; (3) analysis of travel-time and attenuation data from Dr. Michael Richardson's (NRL, Stennis) ISSAMS experiments during SAX99 in the Gulf of Mexico; and (4) controlled wave-speed and attenuation measurements in an "ideal" saturated sediment consisting of spherical, uniform-size glass beads in a laboratory tank. In addition to our sediment research, we have also performed extensive experimental and theoretical work on the underwater sound from the collective oscillations of a bubble plume formed by a plunging water jet.

## APPROACH

*1) An airborne acoustic source of opportunity for ocean-acoustic inversions (field experiments)*  
After SAX99, it was clear that a need existed to extend the measurements of sound speed and attenuation in sediments over as wide a frequency range as possible, and in particular to cover the low frequency band from say 50 Hz to 5 kHz. For several reasons, conventional techniques involving buried sources and receivers are unsatisfactory in this low frequency range. We introduced an alternative approach in which an airborne source of opportunity was used for ensonifying the ocean and the sediment. Most of the received sound is in the form of a sequence of harmonics extending from about 80 Hz up to 1 kHz, the upper and lower frequency limits depending on the operating conditions. On the approach to the sensor station, the harmonics are Doppler upshifted, and Doppler downshifted on departure. The Doppler *difference frequency* is inversely proportional to the local sound speed, that is, the sound speed in the medium in which the sensor is located. Thus, from the difference frequency, the microphone returns the sound speed in air, the hydrophones in the vertical array yield the sound speed throughout the water column, and the buried hydrophone provides an estimate of the low-frequency sound speed in the sediment. Active contributors to these on-going experiments, in addition to myself, are or were: Eric Giddens and Melania Guerra (SIO graduate

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14. ABSTRACT <b>Our sediment research includes four main thrusts: (1) at-sea experiments, including the development of novel inversion techniques, to determine the wave properties of sediments; (2) theoretical analyses, including a) construction of a physics-based analytical model to describe the wave properties of sediments, b) analysis of wave propagation from a moving source in a viscous medium and c) ration-alization of Biot???s theory of waves in porous media; (3) analysis of travel-time and attenuation data from Dr. Michael Richardson???s (NRL, Stennis) ISSAMS experiments during SAX99 in the Gulf of Mexico; and (4) controlled wave-speed and attenuation measurements in an ???ideal??? saturated sediment consisting of spherical, uniform-size glass beads in a laboratory tank. In addition to our sediment research, we have also performed extensive experimental and theoretical work on the underwater sound from the collective oscillations of a bubble plume formed by a plunging water jet.</b>					
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students), Thomas Hahn (SIO post-doctoral fellow), Fernando Simonet (SIO engineer and diver) and Matthew Alkire (undergraduate, SIO summer intern).

### *2a) Analytical model of the wave properties of marine sediments (theory)*

A theoretical model of wave propagation in saturated, unconsolidated porous media such as a marine sediment has been developed, based on the micro-physics of sliding at grain-to-grain contacts. The argument involves the non-linear properties of the thin film of fluid separating adjacent grains. Intergranular interactions give rise to dissipation and dispersion, and these effects are accommodated by a new stress tensor in the Navier-Stokes equation, which, in the usual way, separates into two wave equations, one for compressional waves and the other for shear waves. The theory itself is analytical, yielding simple algebraic expressions for the wave speeds and attenuations. These dispersion relations involve just three independent parameters.

### *2b) A moving source in a viscous fluid (theory)*

In addition to the sound speed, there is potential for using an airborne source of opportunity to recover the attenuation in the sediment. This raises the issue of the nature of the wave field generated by a moving source in a lossy medium. To investigate the essential physics involved, I considered a simple one-dimensional model of rectilinear, unaccelerated source motion through a viscous fluid. A solution of the wave equation was developed, which involved the roots of a cubic, corresponding to the poles of the integrand of a wavenumber integral.

### *2c) Biot revealed (theory)*

The classic theory of wave propagation in porous media, including marine sediments, was published by Biot some half century ago. The essence of the Biot theory is a complicated set of expressions for the complex sound speed in a porous medium. Recently, Kevin Williams re-examined Biot's analysis for a "fluid" medium, that is, one in which the frame modulus and shear modulus may both be approximated as zero. Williams refers to his reduction of the Biot theory as the Effective Density Fluid (EDF) model. Whereas the complete Biot theory involves 12 material parameters (e.g., viscosity of the pore fluid, permeability, porosity, etc.), the EDF model has only 8 parameters, since two complex moduli have, in effect, been removed. At first sight, the presence of 8 material parameters suggests (incorrectly) that the EDF model possesses as many as 8 degrees of freedom. By introducing a formulation based on wave propagation in a viscous fluid, the so-called Modified Viscous Fluid (MVF) model, I was able to show that the EDF model can be closely approximated by a simple algebraic expression for the complex wave speed involving only *three independent parameters*:  $c_0$ , the phase speed in the porous medium in the limit of low frequency, given by Wood's equation;  $c_\infty$ , the phase speed in the medium in the limit of high frequency; and  $f_T$ , the transition frequency separating the low- and high-frequency regimes.

### *3) ISSAMS high-frequency dispersion and attenuation measurements in SAX99 (data analysis)*

Dr. Michael Richardson, NRL Stennis, used his ISSAMS frame to acquire high-frequency (25 - 100 kHz) sound speed and attenuation data for the medium-sand sediment off Fort Walton beach, Florida, during the ONR-sponsored SAX99. His technique involved multiple source and receiver probes, with either tone-bursts or linear FM sweeps. A careful analysis of these data sets was performed at SIO, using only receiver-to-receiver paths, rather than source-to-receiver transmissions. The inter-receiver approach avoids timing errors due to differences between the input to the source and the arrival at a receiver. Travel-times were obtained primarily from a correlation analysis, to yield the sound speed in the sediment, and several techniques were used to estimate the attenuation, including Fourier amplitudes, rms levels, and transposition.

#### *4) Laboratory tank measurements*

Our laboratory tank, half filled with 300 micron diameter glass beads, will be used for high-frequency (20 kHz to 10 MHz), multi-probe measurements of the compressional wave speed and attenuation in a “benchmark” sediment. Participants in these experiments are or were: Eric Giddens and Melania Guerra (SIO graduate student), Thomas Berger (SIO post-doctoral fellow and ONR Young Investigator), Fernando Simonet (SIO engineer).

#### *Acoustic resonances in a bubble plume (theory & experiment)*

A bubble plume formed in a body of water by a plunging jet of water “rings” much like a resonant cavity, generating sound that may be detected by a hydrophone in the water surrounding the plume. Experiments were performed, both in a laboratory tank and in an open body of water, Lake Miramar, to investigate the sound from the plume. The lake experiments were included to confirm that boundary effects were not corrupting the tank measurements. The jet creating the plume consisted of a mix of fresh water and air, the volume fractions of both being carefully controlled and monitored by a system of flow meters and gauges. The observed acoustic spectra exhibited non-uniformly spaced resonance peaks at frequencies that depend on the speed of the flow,  $u_j$ , and the entrainment ratio,  $q$ , defined as the ratio of the volume fluxes of air and water in the jet. The frequency of the  $m^{\text{th}}$  spectral peak follows inverse-fractional power law scalings of the form  $f_m \propto u_j^{-1/2} q^{-1/4}$ . To analyze this phenomenon, a two-component theoretical model of the eigenfrequencies was performed. From a fluid-dynamics argument, based on the conservation of momentum flux in the two phase flow, the speed of sound within the bubbly medium was shown to increase as the square-root of depth in the plume. This sound speed profile was then incorporated into an acoustic analysis in which the wave equation was solved analytically, taking into account the cone-like geometry of the bubble-plume cavity, including the near-rigid boundary condition at the penetration depth, where the bubbly region ends abruptly. Participants in this research were Drs. Thomas Hahn, Thomas Berger (SIO post-doctoral fellow and ONR Young Investigator) and myself.

### **WORK COMPLETED**

#### *1) An airborne acoustic source of opportunity for ocean-acoustic inversions (field experiments)*

To date, five experiments with an airborne source of opportunity have been performed in the Pacific Ocean, about 2 km north of Scripps pier and 1 km from shore, involving a fully instrumented sensor station. A microphone was located 1 m above the sea surface, a vertical array of six hydrophones spanned the 15 m water column, and buried in the sediment, to a depth of about 70 cm, were a hydrophone and a bender (for detecting shear waves). Our preliminary, low-frequency ocean-acoustic inversion experiments have been reported in the Journal of Computational Acoustics and in the European journal, Acta Acustica united with Acustica. These low-frequency experiments have received widespread attention from the ocean acoustics community and have been the subject of several Keynote Addresses at international conferences on underwater acoustics.

#### *2a) Analytical model of the wave properties of marine sediments (theory)*

A unified theory of wave propagation in marine sediments has been developed and published in a series of five papers in the Journal of the Acoustical Society of America. A discussion of the precision correlations emerging from the theory has been published in the Journal of Computational Acoustics.

#### *2b) A moving source in a viscous fluid (theory)*

A one-dimensional analysis of a moving source in a viscous medium has been completed and accepted for publication in the Journal of the Acoustical Society of America.

#### *2c) Biot revealed (theory)*

A rationalized interpretation of Biot's theory of wave propagation in a porous medium has been developed and accepted for publication in the Journal of the Acoustical Society of America.

#### *3) ISSAMS high-frequency dispersion and attenuation measurements in SAX99 (data analysis)*

A detailed analysis of the pulse-transmission data taken with ISSAMS during the SAX99 experiment in the Gulf of Mexico has been performed and has been published in the Special Issue on High-Frequency Sediment Acoustics, IEEE Journal of Oceanic Engineering.

#### *4) Laboratory tank measurements*

Preliminary measurements of sound speed and attenuation in the glass-bead sediment have been performed at frequencies between 25 and 400 kHz. Precision measurements of shear speed and attenuation in the same material have also been attempted.

#### *Acoustic resonances in a bubble plume (theory & experiment)*

Extensive measurements of the sound from a bubble plume have been performed in a tank and in Lake Miramar. A comprehensive theory of the mechanism responsible for the sound has been developed. The experiments on and theory of the acoustic resonances of the bubble plume were the subject of the closing Keynote Address at the 17<sup>th</sup> International Conference on Acoustics, Rome, Italy, 2-7 September 2001. A paper on the bubble plume research, detailing the theory and experiments, was published recently in the Proceedings of the Royal Society, London.

## **RESULTS**

#### *1) An airborne acoustic source of opportunity for ocean-acoustic inversions (field experiments)*

The data we have collected in the past year yield an estimate of  $\approx 1650$  m/s for the sound speed in the fine-sand sediment at the experimental station at a mid-band frequency of 500 Hz. No other low-frequency data are available with which to compare this result, but Hamilton's measurements of wave speeds in similar sediments at higher frequencies ( $> 3$  kHz) returned similar values. In addition to obtaining sediment information, we have demonstrated that the new technique is capable of providing the sound speed profile in the water column, as well as source parameters, notably source speed and altitude, along with atmospheric conditions, such as wind speed at the source altitude.

#### *2a) Analytical model of the wave properties of marine sediments (theory)*

My newly developed theory of wave propagation in marine sediments accurately represents the compressional-wave speed and attenuation data over a wide range of frequencies. It also matches the few shear-wave data that are available. The high quality of the match to dispersion and attenuation data is encouraging in view of the highly constrained nature of the theoretical predictions: the dispersion relations for the compressional and shear waves involve just three unknown constants. These unknowns may be determined by comparison with three of four variables: compressional speed, compressional attenuation, shear speed, or shear attenuation. As a test of the theory, the prediction of the fourth variable is then compared with the corresponding observation, and excellent agreement is found.

#### *2b) A moving source in a viscous fluid (theory)*

An apparently straightforward analysis of the wave field generated by a moving source in a viscous medium actually contains several subtleties, leading eventually to the conclusion that three waves are present: an attenuated, Doppler-upshifted propagating wave on the approach; an attenuated, Doppler-downshifted propagating wave on the departure; and an *evanescent wave* which appears at the instant

the source passes the receiver. The up- and down-shifted propagating waves have the same Doppler frequencies as they would in an inviscid fluid. A new result is that the attenuation of these waves is highly asymmetrical, being greater on approach than departure to a degree that depends on the Mach number of the source. In other words, the dissipation and source motion are coupled together to determine the attenuation. The presence of the evanescent wave is a curious phenomenon and one that has not been recognized before. It can exist only when dissipation and source motion are both present, and then extremely briefly. In most circumstances, the evanescent wave will have no practical significance; but the asymmetry in the attenuation of the propagating waves may have important practical implications in connection with the interpretation of sound from rapidly moving acoustic sources.

#### *2c) Biot revealed (theory)*

The three parameters,  $(c_o, c_\infty, f_T)$  of the MVF model have been expressed as combinations of the 8 material parameters in the EDF model. From the new formulation, it is clear that the Biot theory is highly constrained, yielding dispersion curves with very simple forms: the attenuation varies as the square of frequency below the transition frequency and as the square root of frequency above; and the sound speed is constant at low frequencies, transitioning to another constant value above the transition frequency. No other functional forms are available for the dispersion curves from the Biot theory. In particular, however much the 8 material parameters are adjusted, it is not possible to obtain an attenuation that varies linearly with the frequency from Biot. Moreover, the Biot theory is very limited in terms of the information that it may yield when used as the basis of an inversion for the material properties. For instance, the permeability and viscosity appear only as a ratio, and then only in the expression for the transition frequency. Thus, without prior information on either the permeability or the viscosity, it is not possible to perform an inversion based on Biot which returns the values of the permeability and the viscosity independently.

#### *3) ISSAMS high-frequency dispersion and attenuation measurements in SAX99 (data analysis)*

Over the frequency band (25-100 kHz) covered by the ISSAMS data, dispersion in the sediment off Fort Walton Beach, Gulf of Mexico, was found to be weak and the attenuation scaled as the first power of frequency. Both results are consistent with measurements made by other investigators during SAX99. Two theories, by Biot and by Buckingham, of wave propagation in marine sediments were compared with the data. Both could be fitted to the dispersion results reasonably and Buckingham's prediction of attenuation varying linearly with frequency accurately matched the observations over the full frequency range. Biot's predicted attenuation, however, shows a frequency dependence that is characteristic of a viscous fluid, varying as frequency squared at low frequencies and as the square root of frequency above some threshold frequency. Such behavior is not exhibited by the data.

#### *4) Laboratory tank measurements*

Our early experiments on the glass-bead sediment returned sound speeds which depended very weakly on frequency, with values close to 1750 m/s.

#### *Acoustic resonances in a bubble plume (theory & experiment)*

The expression we derived for the frequencies of the lowest-order longitudinal modes of the bubbly cavity exhibits the same inverse-fractional power-law scalings as observed in the experiments. The experiments and theory are consistent with the conclusion that the scaling of the eigenfrequencies with the inverse square root of the jet velocity stems from the square-root sound speed profile within the biphasic plume. This is believed to be the first time that the sound speed profile within a bubble plume has been quantitatively linked with detailed spectral features of the sound field external to the plume.

## **IMPACT/APPLICATIONS**

Our theoretical and experimental research on the wave properties of sediments is multi-faceted. Taken as a whole, the research is starting to provide new insights into the fundamental physics of waves in porous media. Theory and experiment are progressing together, each building on the other, to provide an internally consistent picture of surprisingly complex phenomena.

## **TRANSITIONS**

Several research groups in the USA and elsewhere are using the results of our theoretical work in their own programs, including investigators at the Applied Physics Laboratory, University of Washington, the University of Hawaii, NRL Stennis and in UK government research laboratories. Our sub-surface instrumentation techniques are being adopted by the US Air Force to monitor the underwater sound of sonic booms from rocket launches on the island of Kauai.

## **RELATED PROJECTS**

### **U.S.A.**

1. Dr. Michael Richardson, N.R.L., Stennis, and I are continuing to collaborate on the interpretation of sediment wave property data obtained using his ISSAMS frame. This includes the re-assessment of travel-time measurements and the development of techniques for making high-accuracy sound speed and attenuation measurements in sediments.
2. I was an active participant in the ONR supported SAX99 experiment conducted in the Gulf of Mexico and will be involved in the follow-up experiment, SAX04, planned for 2004. Chief Scientist in both experiments is Dr. Eric Thorsos, APL, University of Washington.
3. Dr. Alex Tolstoy and I are collaborating on the application of Matched Field Processing to hydrophone data generated by a rapidly moving airborne source. We hope to apply MFP to the data we have already collected at SIO to obtain a quantitative description of the ocean-sediment environment in the vicinity of the receivers.
4. Prof. Giorgio Gratta, Stanford, and I are working on the underwater acoustic detection of extremely high energy neutrinos. Acoustic data for this project are being provided the U.S. Navy's AUTECH range off Andros Island, Bahamas. (Paper published in Astroparticle Phys.)

### **Canada**

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on measuring the interface-wave properties of the bottom using a “hush gun”, a type of quiet air gun. In particular, we plan to determine the low-frequency (100 Hz to 1 kHz) sound speed in the sediment from the head wave, probably at a site just north of Scripps pier, off La Jolla, California.

### **United Kingdom**

1. Dr. Sam Marks, Defence Evaluation and Research Agency (DERA), Winfrith, holds an extensive data set of sediment properties from world-wide locations. We are currently exploring ways of using these data to help in the theoretical development.

2. Dr. Nicholas Pace, University of Bath (currently at SACLANTCEN, La Spezia, Italy) and I are discussing the possibility of using an airborne source for low-frequency measurements of sediment properties in the Mediterranean.
3. Dr Alastair Cowley, DERA, Winfrith is collaborating with me on phased array techniques applied to acoustic daylight imaging. He and his team of engineers recently conducted tests in San Diego Bay using our ADONIS array head of 128 hydrophones with their high-speed beamformer. This phased array system, without the spherical reflector that was used in our original acoustic daylight experiments, yielded recognizable images of targets at ranges of approximately 10 m solely from the acoustic illumination provided by the ambient noise in the ocean.

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### **HONORS/AWARDS/PRIZES**

My graduate student, Eric Giddens, was awarded First Prize for Best Student Paper by the Underwater Acoustics and Engineering Acoustics Technical Committees at the 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 December 2002.